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The Approach to Equilibrium in a Reflex Triode

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Analytic and PIC descriptions are combined to provide a theory of reflex triode operation in and near the steady state. The spectrum of reflecting electrons is examined both for a steady input of electrons into the scattering foil and for the dynamically evolving process of achieving the reflexing equilibrium. Simple approximations to analytic modifications of the classical theory then offer a more versatile theory of the reflexing system.

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THE APPROACH TO EQUILIBRIUM IN A REFLEX TRIODE

Introduction

Unique in the spectrum of opening switch concepts, the reflex triode[1,2] offers the possibility of triggering the opening phase to control the overall synchronism of a inductive store pulser. The basic triode construction (and even its more elaborate variations) has an attractive simplicity when compared to the complex source hardware for plasma erosion opening switches, density controlled opening switches or plasma filled diodes. In common with the plasma filled diode, the reflex triode switch is its own load and thus minimizes the inductance "downstream" of the opening switch, a property long known to be helpful in any inductive store concept.

There are two principal concerns in bringing such switch into routine use. A relatively minor problem is the requirement for an axial magnetic guide field, which leads to auxillary coil and shielding hardware. The more critical problem is the fact that the larger currents are not presently achievable, nor credibly implied by the heretofore successful scaling laws concerning the "anomalous gap closure", which limits the peak conduction phase current.

The physics that determines the upper current limit for the conduction phase is not fully understood at present. The theory presented here seeks (i.) to establish a more complete physical basis for reflex triode switch operation, (ii.) to refine, in the context of real devices, some of the classical notions held from early equilibrium theory and, (iii) to provide some conceptually simple models which allow estimates

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particle approach readily incorporates sufficient generality to treat the global switch behaviour and to provide qualitative guidance as to the relative importance of various phenomena. The continuum theory approach readily captures, quantitatively, (i) the observed current density enhancements in the conduction phase and (ii) the typically observed opening phase current and voltage levels – even though we use very simple ideas to model the opening process.

A diagram of a typical reflex triode is shown in Figure 1, annotated with the usual variables for the familiar Child-Langmuir diode theory and some new ones.

REFLEX TRIODE SYSTEM VARIABLES

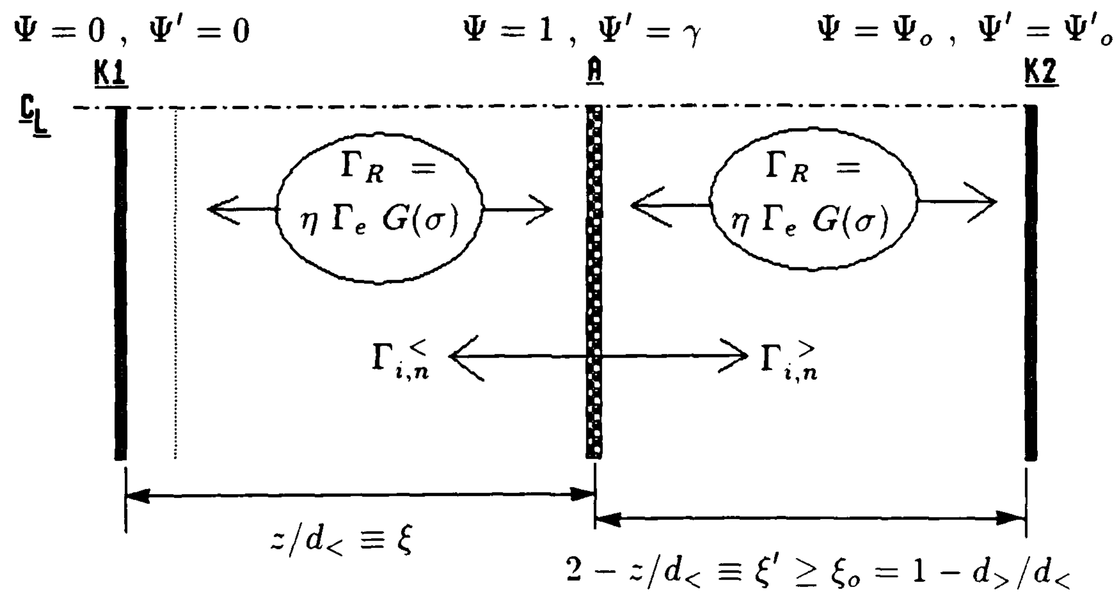

Figure 1

Here Γ_R is the reflexing electron flux (unidirectional), $\Gamma_{i,n}$ are the ion and neutral fluxes generated at the anode, $\Psi(\xi) \equiv V(\xi)/V_o$ and $\Psi'(\xi) \equiv (\frac{d}{V_o})\frac{dV}{dz}$ arc the normalized potential and field profiles. The boundary conditions at each electrode are indicated. The unsubscripted γ factor is a measure of the mean field at the anode surface required to extract an ion – due to charge exchange drag. Drag factors in the "vacuum" region, also discussed below, are subscripted γ variables.

for the effects of "anomalous gap closure" or alternate hypothetical opening mechanisms on the predicted device waveforms.

This requires that we address, using a quasi-steady state Vlasov formulation, and a dynamic PIC formulation, some important questions which arise in connection with the reflex triode switch:

- *Does charge exchange with neutrals provide the rapid gap closures observed; how can one derive and improve the observed scaling laws?*
- *What are the fundamental limits on the current density? Are they determined by the electrode physics, microinstabilities, or electron neutral collisions?*

We will first build an extension of the "classical" theory to develop those ideas needed in connecting the steady state, single particle Vlasov metaequilibria to slow timescale changes in the boundary conditions and reflexing spectra. We will illustrate some connections and contrasts between the PIC treatment and the continuum theory. Next we will show the development of a circuit model which addresses the initial buildup phase of the current and the transition from low to high impedance. Using some simplified results of the more complicated models we will compare the circuit model picture to experimental data.

Phenomenology of the Reflex Triode

Present reflex triode switch devices are generally operated on the early phase of the current pulse discharging energy into the storage inductor. The triode first presents a high voltage to the driver as the electron population builds up and begins to oscillate (reflex) through the foil anode. Those electrons transiting the primary gap (the so-called A-K1 gap) at high energy are stopped by the secondary cathode and begin to charge it negative relative to the anode. This process continues until there is a detailed balance between received and re-emitted electron current

and a floating potential is established on the secondary cathode K2. This floating potential usually exhibits one or more positive voltage steps during the conduction phase, probably due to bursts of ion current from the anode. The ion current is, of course, unidirectional – no ions are re-emitted. Yet, so long as there exists a voltage difference on the A-K2 gap which is large enough to boost an electron re-emitted from K2 to a one range energy in the foil anode, viz. $\geq 10kV$, the reflex electrons can continue to populate a spectrum of energies above that required for capture and thereby enhance the ion emission from the anode.

It is the ion emission that is the key to the low impedance state which then develops after a few tenths of μs. For, while the ion current is relatively small (particularly for the true triode geometries), the ion space charge in the gap neutralizes the primary electron space charge and shortens the effective gap spacings near each electrode.

The low impedance state would persist forever (in principle) but always falls prey (in practice) to some catastrophe associated with the movement of the floating conductor nearer the anode potential. The opening phase occurs too soon in the driver pulse to offer effective power transfer and fails to follow previously observed conduction time scalings, based on the notion that charge exchange neutrals fill the triode and short the gaps.

Basic Relations from the Vlasov Picture

In contrast to the highly discrete particle code approach, discussed later, the treatment presented first relies upon the continuous representation of the reflex triode plasma by a single particle distribution function. Both techniques have serious limitations and the relative merits of either can be discussed at length, but the best use of such diversity appears to lie in cross comparison. Briefly stated, the discrete

The electron energy spectrum is $g(\sigma)$ $(1 \geq \sigma \geq \Psi_o)$ *and arises through multiple scattering events in the anode foil. In these terms two basic variables are the bipolar Child-Langmuir current,* $I_o = 2.334 \cdot 10^{-6} \frac{A}{d_<^2} V_o^{3/2}(1 + \sqrt{Zm_e/m_i})$, *and the ratio of ion to electron current,* $j_i/j_e = \alpha\sqrt{Zm_e/m_i}$.

Electrons scattered in the anode with each reflexing passage populate a distribution f_e *which can be projected onto the subspace* $[W_o \otimes \tilde{\mu}]$ *of (gyrokinetic) adiabatic invariants*[3]

$$W - \tilde{\mu}B_z \;=\; \frac{1}{2}m_e V_z^2 - e\Phi \;=\; W_o \;= -eV_o\sigma \;,$$

$$\tilde{\mu} \;=\; \frac{m_e w^2}{2B_z}(1 - \epsilon(\dot{v}_{z,\theta})) \;\;.$$

These variables form a "good" set because, even though $\tilde{\mu}$ *is only approximate, it will be "used" only for one electron transit in and out of the random scattering process, since we fiduciate the constants of motion to the anode plane. The capture energy at the anode is thus mapped to the limit* $W_o \to -eV_o$ $(\sigma = 1)$, *while the limit* $W_o \to 0$ $(\sigma = 0)$ *confers the full A-K1 voltage to an primary beam electron. The modification to* $\tilde{\mu}$, *due to the largely axial acceleration* $\dot{v}$ *is obtained only in the limit that the magnetic field due to the conduction phase current is competitive with the guide field in the switch.*

The "free streaming" electron populations then admit a projection operation $\Pi_{W_o} f_e = f_e(\mathbf{x}, \mathbf{v}|\sigma)$ *such that*

$$j_e(x) = e\Gamma(x) = e\int d\sigma \frac{d\Gamma(x,\sigma)}{d\sigma} \equiv e\int d\sigma \;\Big[\int_{v_z>0} d^3v \; v_z f_e(\mathbf{x}, \mathbf{v}|\sigma)\Big] \;,$$

separating the reflexing current into subcomponents. The subcomponents may be considered either as discrete $\delta\sigma$ *or differential* $d\sigma$ *sections of the distribution function defined on subsets of the* $[\mathbf{x}, \mathbf{v}]$ *domain. The important property is that the Vlasov*

equation is trivially satisfied for any subcomponent $f_e(\mathbf{x}, \mathbf{v}|\sigma)$, *in the free streaming region.*

A formal derivative with respect to W_o *or* σ *defines the usual spectrum of free electron energies,* $\frac{dS(W_o,z)}{dW_o} \equiv \int d^3v \Pi_{W_o} f_e$, *which must satisfy two* a priori *constraints.*

(i.) The integral over all energies must provide a measure of the total number of reflexing electrons. With $\Gamma_e \equiv \int_{v_z>0} d^3v\ v_z f_e(z=0, \mathbf{v}|\sigma=0)$ *, the emitted source flux at K1, the normalization used here is*

$$\Gamma_{Reflex}(\sigma) = \int_0^\sigma d\sigma_1 \frac{d\Gamma(x,\sigma_1)}{d\sigma_1} = \eta\Gamma_e\ G(\sigma) : G(1) = 1\ .$$

(ii.) The gradient with respect to the energy ratio σ *must represent a positive definite electron probability density*

$$\frac{d\Gamma_{Reflex}}{d\sigma} = \eta\Gamma_e g :\ g(\sigma) \equiv \frac{dG}{d\sigma} = \int_{v_z>0} d^3v\ v_z \Pi_{W_o} f_e\ \geq 0\ .$$

Any time dependence of the reflexing process or the injection flux Γ_e *is reflected mostly in the time development of* $\eta\Gamma_e$ *and to a lesser extent in the spectral form factor* g. *It will be shown that very small changes in* η *near some critical value can make enormous changes in* Γ_e.

<u>Steady State Reflex Triode Model</u>

In order to make contact with some of the phenomena seen in the reflex triode switch one must extend the steady state theory[4] *of Prono, Creedon,* et.al., *to include*

i. *more general emission boundary conditions, e.g. charge exchange presheath effects;*

ii. *asymmetric potential distributions and gap spacings;*

iii. *realistic foil scattering spectra (of parallel energy);*

iv. *electron and ion drag mechanisms;*

v. *deterministic opening mechanisms, viz. changes in the internal metaequilibrium state which raise the impedance quickly.*

Only this sort of extension can provide a simple test bed for experimental comparison that incorporates the results of the PIC code REFLEX whenever possible.

The usual method[5] *for examining space charge limited flow is to determine the velocity of a current carrier as a function of the local potential value. Adopting the simple notion that the "average" charge carrier may be subject to some modest drag forces – whether from collective effects or direct collisions – a "test particle" variation on this theme can be constructed.*

Let $\mathcal{T}(\xi)$ *represent the kine'ic energy of a particle relative to its free acceleration value over the full gap, viz.* $mv^2/2qV_o$. *When the drag force is modeled as proportional to the kinetic energy divided by a "mean free path for momentum transfer" or "damping length"* (λ), *the equation of motion can be integrated once to yield*

$$\frac{d\mathcal{T}}{d\xi} \pm 2\gamma\mathcal{T} = \Psi' ,$$

where $\gamma = d/\lambda$ *and the prime also denotes* $d/d\xi$. *The damping length scale is now just a parameter that can be obtained from auxillary models. Denoting the various drag processes by* $\gamma_{i,e}$, *the kinetic energy becomes*

$$\mathcal{T}_e(\xi) = \mathcal{T}_e^o e^{-2\gamma_e\xi} + \int_o^\xi d\xi_1 \; e^{2\gamma_e(\xi_1-\xi)} \; \Psi'(\xi_1) ,$$

and

$$\mathcal{T}_i(\xi) = \mathcal{T}_i^o e^{-2\gamma_i(1-\xi)} + \int_\xi^1 d\xi_1 \; e^{2\gamma_i(\xi-\xi_1)} \; \Psi'(\xi_1) .$$

In the limit that $\nabla \cdot J = 0$, *the kinetic energy terms can represent quasi-steady fluxes of electron and ion space charge in the Poisson equation. The first integral can be obtained to provide an integral equation formulation for* $\Psi'(\xi)$

$$\Psi'(\xi) = \frac{4\beta^{1/2}}{3} \left[\frac{4\eta}{3}\mathcal{F}(\Psi,\Psi_o) + \mathcal{T}_e^{1/2}(\xi) + \alpha\mathcal{T}_i^{1/2}(\xi) + \right.$$
$$\left. \gamma_e \int_o^\xi d\xi_1 \mathcal{T}_e^{1/2}(\xi_1) - \alpha\gamma_i \int_o^\xi d\xi_1 \mathcal{T}_i^{1/2}(\xi_1) \right]^{1/2},$$

where cold emission has been assumed and the spectral contribution $\mathcal{F}$ is given by

$$\mathcal{F}(\Psi,\Psi_o) = \frac{3}{2}\int_o^\xi d\xi_1 \Psi'(\xi_1) \int_o^{\Psi(\xi_1)} d\theta \, \frac{g(\theta)}{\sqrt{\Psi-\theta}} \, .$$

The integral over the spectrum can be simplified – via Liebniz rule, a partial integration and a reversal of integration order – to give

$$\mathcal{F}(\Psi,\Psi_o) = g_o(\Psi-\Psi_o)^{\frac{3}{2}} - \int_{\Psi_o}^{\Psi} d\theta g'(\theta)(\Psi-\theta)^{\frac{3}{2}} \; .$$

The constraint $\Psi \geq \Psi_o$ is understood; $\mathcal{F}$ vanishes elsewhere.

In the limit of zero damping, strict space charge limited ion emission, and symmetric potentials this formulation reduces to that of Creedon. If furthermore, the reflexing flux is set to zero, there obtains a full reduction to bipolar Child-Langmuir theory.

When one can simplify this integral equation because the modifications due to the drag effects are very small, viz. $\gamma_{e,i} \ll 1$, then the integrated terms above reduce to simple mean valu: estimates. On the [A,K1] domain the normalized electric field is then approximately

$$\Psi' = \frac{4}{3}\beta^{\frac{1}{2}} \left[d_e\sqrt{\Psi} + \alpha(\exp -\gamma_{ex}/2)[(\sqrt{(1-d_i\Psi)}-1)] + \frac{4\eta}{3}\mathcal{F}(\Psi,\Psi_o)\right]^{\frac{1}{2}}_{\mathcal{G}(\Psi)} \, .$$

Here the effects of damping mechanisms are approximated by d_e and d_i,

$$d_e = \sqrt{(1-2\gamma_e(1 - \exp -\gamma_e)} \, ,$$

$$d_i = (\exp\gamma_i)(1-2\gamma_i) + 2\gamma_i \, ,$$

where the γ's represent, as defined above, the reciprocal mean (dimensionless) free

path for momentum transfer and the reductions to the classical formulation are preserved. To stay sensible, these rough forms involving the damping factors must be confined to the domains $\gamma_e \leq 0.864$ and $\gamma_i \leq 0.5$

The continuity of Ψ' determines the normal K2 electric field parameter, which figures in the gap breakdown dynamics, $\Psi'_o(\Psi_o, \xi_o, \alpha, \beta)$, as

$$\Psi'_o \;=\; \frac{4}{3}\beta^{\frac{1}{2}}\;[d_e\sqrt{\Psi_o} \;+\; \alpha(\eta, \mathcal{F}, d_e, d_i, \gamma)(\sqrt{(1-d_i\Psi_o)}-1)]^{\frac{1}{2}}\;.$$

Usually the parameter η, which measures the overall strength of the reflexing flux relative to the primary flux from the cathode (K1), is considered to be a function of the voltage on the primary gap and thus increases in rough proportion to the number of reflexing passes this voltage would imply for a given foil anode. In an actual triode, allowing for the re-emission of electrons from the floating conductor, this simplification no longer holds. In general the re-emitted population is bounded above in energy by the value of the floating potential difference $1-\Psi_o$. As $\Psi_o \rightarrow 1$, particularly in the case of pure space charge limited ion emission ($\gamma \rightarrow 0$), the electron population is held to such low energies that the flux ratio η can never be much larger than 1 even if electrons reflex 10 times or more through the anode. If one defines $\mathcal{F}(1, \Psi_o) \;=\; f(1, \Psi_o)\sqrt{1-\Psi_o}$ then the largest allowed value of η is constrained by

$$\eta_{max} \;\leq\; \frac{3}{4f}\Big[\frac{1-\sqrt{\frac{1-\sqrt{\Psi_o}}{1+\sqrt{\Psi_o}}}}{1-\sqrt{(1-\sqrt{\Psi_o})(1+\sqrt{\Psi_o})}} \;+\; \frac{9/16\gamma^2}{\sqrt{1-\Psi_o}}\Big],$$

in order to retain a real solution at the entry point to the (spatially) bounded reflexing region in the primary gap.

Only because we have approximated the integral equation character of the problem can the A-K1 current be determined by the familiar quadrature

$$\beta^{\frac{1}{2}} \;=\frac{3}{4}\int_0^1 \frac{d\theta}{\mathcal{G}^{\frac{1}{2}}(\theta)} \;\approx\; \delta\theta\frac{\ln(4\mathcal{G}_+/\mathcal{G}_o)}{\mathcal{G}_+^{1/2}}\;.$$

Here β measures the current density enhancement over a Child-Langmuir bipolar diode – due to the reflexing population as measured by the flux ratio η. In exactly the same way as the "classical" formulation, this quadrature implies essentially singular current in the allowed metaequilibrium states if the parameter η approaches a critical value. Such a critical value exists for all $\Psi_o < 1$, viz. low impedance states persist until the absolute value of the A-K2 voltage can't get an electron to a 1 range energy in the anode. Even though η_{max} can drop close to 1 for $\Psi_o \to 1$ there always exists a value $\eta_{crit} < \eta_{max}$ which offers the singular state. The logarithmic nature of this singularity has been indicated in the formula above, where $\mathcal{G}_o$ represents the true minimum value of the (dimensionless) electric field profile function and $\mathcal{G}_+$ it's value on the boundaries of a domain $\delta\theta$ in the potential. Under what conditions real experiments can approach this sort of equilibrium is simply unknown, but the laboratory experience does indicate that a high level ($\beta \geq 1000$) of current enhancement is obtained routinely. From the theory presented here this observation implies that the interior electric field is being shielded to better than a few parts in 10^7 relative to its peak value near the electrode surfaces. Indeed the modest β field structure is no different from that characterizing very large β values. Figure 2 shows a $\Psi_o = 0.5$, $\beta = 224$ triode field profile. In this case the value of η differs only slightly from the critical value at which $\beta \to \infty$. Those few signifcant figures in η correspond to charge variations of at least several hundred million electrons per cc in the denser space charge regions, well above thermal fluctuation levels.

The simulation experience confirms the global robustness of this low impedance state, but does not resolve the large current density enhancements one observes. The particle model is limited by random noise in its ability to suppress the interior field values on its grid. Moreover, the several hundred million electrons variation noted above corresponds to only a few code macroparticles. In resonance with the equilibrium picture, the particle code does not exhibit β values much in excess of 200!

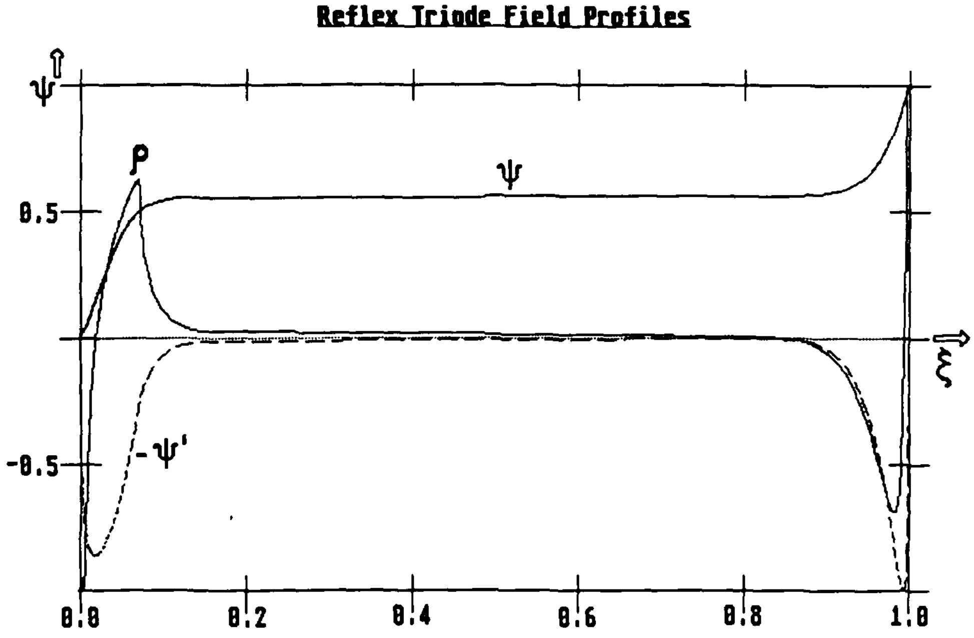

Figure 2

On the other hand, the general character of the simulation's Vlasov phase space is in good agreement with a similar picture, Figure 3, drawn from the equilibrium theory, showing the two beam populations and the contours of constant σ, again for the same parameters as in the previous figure. The probability density $f_e(\mathbf{x}, \mathbf{v}|\sigma)$ is also constant on each of these contours if there is a true steady state, but in any case these contours are the Vlaxov characteristics for the problem. The primary feature to note here is that, for a real triode with $\Psi_o > 0$, the hole in phase space between the beam and reflexing populations will be depleted by the circuit constraints and filled by turbulence in the primary beam and reflexing electron population. When and at what level the balance is struck will be shown in the PIC simulations.

It may be argued that such a delicate balance ($\pm 10^8$ electrons) is not physically accessible to any real system and, moreover, that inferences drawn concerning the operating point and the sensitivity of this model to boundary condition changes could not therefore be expected to hold under laboratory conditions. Ideas of this

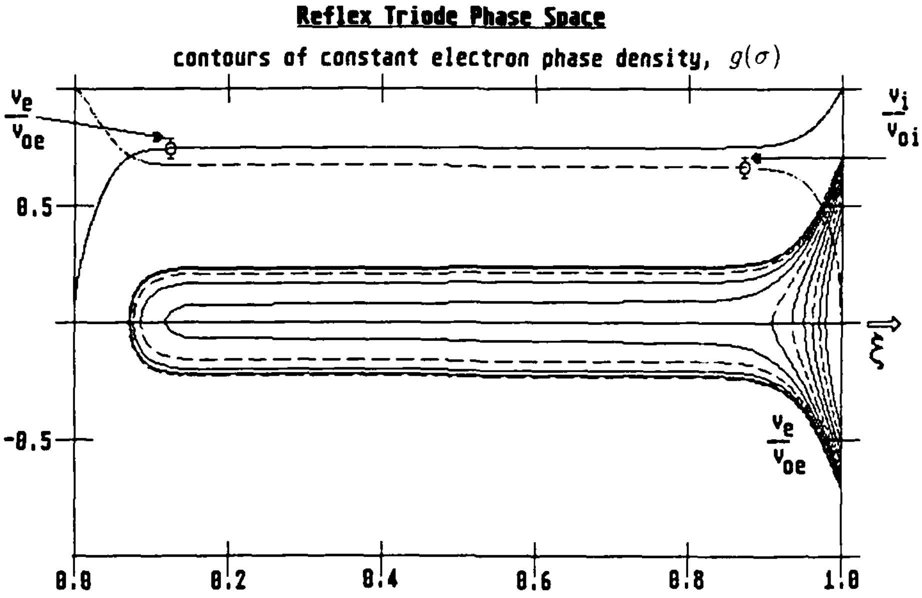

Figure 3

nature also require proof, however appealing they may be intuitively. In this regard one fact must be kept in mind – the sensitivity of the "nearly singular" equilibria is logically inseparable from their ability to explain the large current density enhancements. If these sensitivities and other properties are unsatisfactory, then another explanation for the enhanced current density must be proposed and examined. The only model that explains the current density enhancement is, at present, the "classical" one or the improved version discussed above. Because the equilibrium model exhibits sensitivity to boundary conditions, interior field extinction levels, or dissipative processes, then experiments can and should be designed to test these ideas insofar as it is practical to do so.

Auxillary Models

The Vlasov descriptions just discussed require as input several nontrivial bits of physics from either experiment or other theoretical treatments. Chief among these

is a scattering model for the effective spectrum of electron energies. The next most critical is an estimate for the flux of fast charge exchange neutrals Γ_n *produced at the anode and probably responsible for the rapid gap closure phenomena. Finally one must consider the magnitude of various drag mechanisms on both ions and electrons, the local field strengths and neutral pressures near K2 which will figure in the gap shorting time, and the boundary condition evolution at the anode.*

Aside from the steady conduction phase evolution of η *to values near the singular point, one finds that (from an operational point of view in fixing* β*) all such auxillary physics changes (time variable anode boundary conditions, reflexing population changes, or damping processes) are imbedded – via the spectrum* $\mathcal{F}$ *and the various* γ*'s – in the single parameter* $\alpha(\eta, \mathcal{F}, d_e, d_i, \gamma)$

$$\alpha = \frac{(1+\gamma_e/2)d_e \; + \; f\frac{4\eta}{3}(1-\Psi_o)^{1/2} \; - \; 9/16\gamma^2}{e^{-\gamma_i/2}[1-(1-\gamma_i/2)(1-d_i)^{1/2}]} \; ,$$

which determines the relative level of ion current in the triode by forcing the boundary condition on the electric field at the anode.

Generally as α *increases from 1 the ion space charge brings* β *up, and conversely. Among the factors that lower* β *by reducing* α *are (i) any reduction in ion emission caused by anode resistance* γ*, (ii) any movement of* Ψ_o *towards 1, and (iii) any reduction in the parameter* η*. The direct effect of the approximate damping factors on* $\beta(\alpha)$ *is to increase it, presumably due to the longer time spent by a particle in the gap. On the other hand one expects the exponential character of the damping to come into play as the* $\gamma_{e,i}$ *terms exceed their present constraint values and lower* α*. In addition, the drag of slow, reflexing electrons on slow moving ions and neutrals late in the conduction phase would be manifested in a direct lowering of* η *by pushing more electrons to low energy domains. A good evaluation of the drag effects requires the solution of the full integral equation.*

Evaluating the spectral convolution

One way to obtain a spectrum is to use REFLEX's Moliere[6] *scattering model which operates in the limit where the mean squared scattering angle is larger than the usual Rutherford result. Here the (relativistic) electrons exhibit a total scattering cross section of the general form:* $\sigma_T \propto Z^{1/3}(Z+1)/v^2$. *In such a mylar foil, for example, a 10keV electron has a 2 micron range. The scattering model has been benchmarked with the TIGER code, c.f. J.M. Les and J. Ambrosiano*[7].

The spectrum of energies $g(\sigma)$ *can be determined over the full reflexing voltage range, and used to set* $\mathcal{F}$. *In Figure 4 an overlay of many such flux spectra shows an essentially universal shape for all the voltages examined* ($V_o \rightarrow 100kV$), *only the normalization changes and the* η *parameter holds this information in any case. A power law fit* ($a \approx 0.68$) *is observed*

$$g(\sigma) \approx \frac{a+1}{(1-\Psi_o)^{a+1}}(1-\sigma)^a$$

and this result allows an analytical evaluation of the spectral convolution. One finds, with $\rho = \frac{\Psi - \Psi_o}{1-\Psi_o}$,

$$\mathcal{F}(\Psi, \Psi_o) \;=\; (1+a)\sqrt{1-\Psi_o}\left[\rho^{3/2} \;+\; \frac{2a}{5}\rho^{5/2}\;{}_2F_1\left({1-a \;\; 1 \atop 7/2}\Big|\rho\right)\right].$$

This spectrum is the asymptotic result for the pure scattering model where the input flux (at $\sigma = 0$) *is held fixed and no collective plasma effects are active in changing the distribution. Modifications of this spectrum are discussed below in connection with the PIC code simulations.*

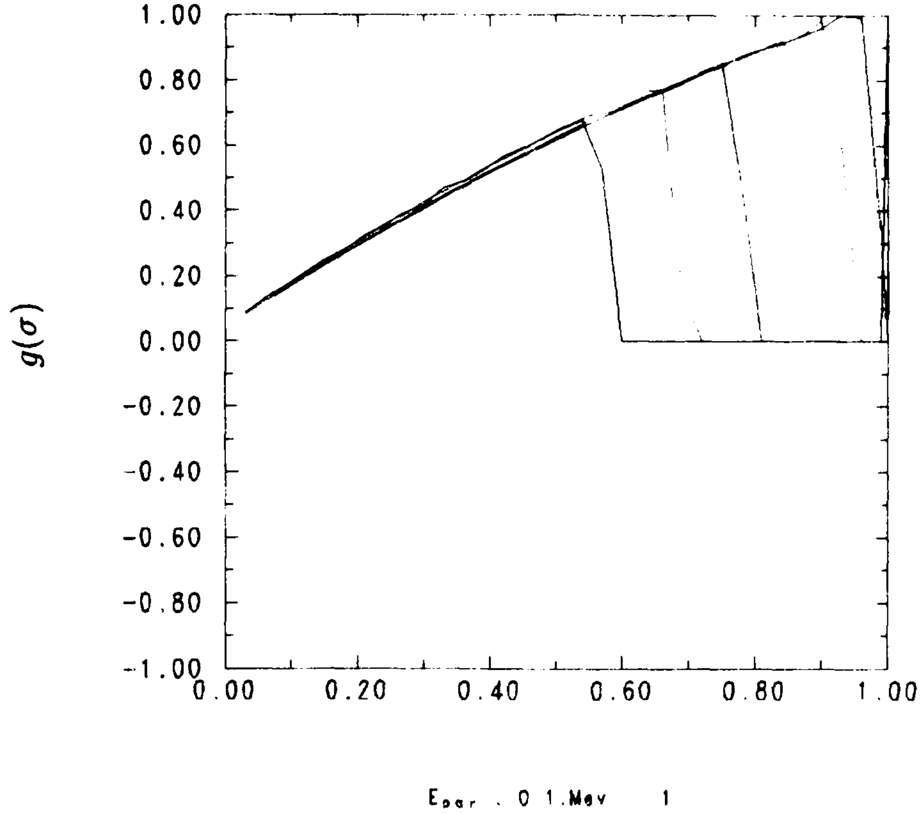

Figure 4

Evaluating the ion charge exchange sources

A Monte Carlo code[8] has been developed which treats the ion charge exchange process through a given background of neutral gas; the benchmarks and early applications are encouraging – the correct spatial dependence of neutral flux is predicted for the case of constant cross section. The input required is a neutral density spatial profile, an electrostatic potential function, or a flux of hot ions, and an appropriate cross section. The output is a neutral flux profile and energy distribuion which can be used as a first step in calculating the scaling laws for the gap closure. Some simple estimates for the velocity of charge exchange neutrals have been obtained[9]. While these are of limited generality, the code and analysis would predict final neutral velocities in the range of $20 \rightarrow 60 cm/\mu s$ *for the expected field strengths in a typical* $\beta \approx 1000$ *system. This corresponds to the acceleration of hydrogen ions*

over a potential of a few hundred volts to perhaps a kilovolt in a small fraction of a centimeter. We also find a weakening dependence of this neutral velocity with ion layer thickness. After the layer is thickness (x_o) is large enough to get ions up to the rollover energy of the charge exchange cross section ($W_o \approx 10keV$) in the ambient electric field, viz. when $qEx_o \approx W_o$, then the final velocity is very weakly dependent on the ambient E field. Moreover, for the thinner layers, the neutral energy scales linearly with the electric field – in agreement with rough analytic scaling laws and the empirical scaling rule $t_S^{\frac{3}{2}} j^{\frac{1}{2}} \propto d_{AK1}$. At these velocities the observed time difference t_S between the onset of opening and the "anomalous closure" of the main gap – with the consequent prompt lowering of the triode voltage – is accounted for by the difference in gap spacing. For typical bank and gap parameters one would expect this time difference to be about 0.10 $t_{\frac{1}{4}}$.

Simulating the Approach to Steady State

Using the REFLEX code one can determine the spectrum and flux ratios that arise in a triode system as it comes into a fully developed reflexing state. As the electron population settles down and establishes the two sheaths, the spectrum relaxes as well, showing a marked smoothness in the time averaged population at any particular value for the σ parameter. The time average is carried out over ten or more electron transit periods, as estimated from the local simulation parameters.

As a direct comparison with the Vlasov description, the secondary circuit is isolated resistively so that a fixed fraction of the primary gap driver voltage tends to build up over time. The steady state achieved tends to oscillate about a secondary voltage value greater than the primary, but collective effects can force rather wide excursions about this mean.

If the secondary voltage is greater than the primary ($\Psi_o < 0$), then the re emitted electrons from K2 can easily flow back into the primary gap although most of the population is turned around without ever striking K2. A reflexing state is

achieved with a rather broad phase space measure in v_z near the anode, and the time averaged spectrum is peaked near $\sigma = 0$ and is monotonically decaying elsewhere.

For ($\Psi_o > 0$) the reflexing population is narrower in v_z near the anode and the quality of reflexing is improved in that more primary current is drawn and the voltage is further reduced on the primary gap. As shown in Figure 5a where contours of equal particle population are plotted on the time and energy domain, the time history of the energy constant is dominated by the detailed wave particle interaction. The phase space hole is energetically possible but gets filled in rather completely by microturbulence. The potential profile (Figure 5b) is shown for K2 well above the K1 potential, but the phase space is clearly populated in the region where the gap should be, as is evident in Figure 5c, where the time averaged spectrum $g(\sigma)$ is shown. The spectrum shows a more pronounced plateau near $\sigma \approx \Psi_o$ but the region near $\sigma \approx 0$ is heavily populated by particles of essentially full primary gap energy. The scattering model may be responsible here insofar as the Moliere limit is going

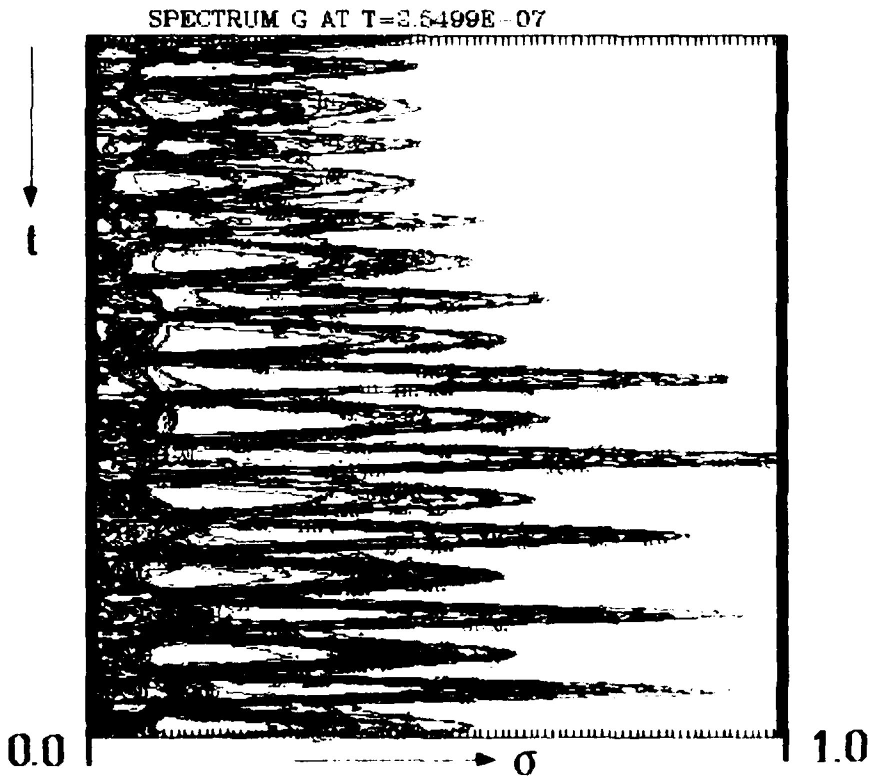

Figure 5a

to be progressively violated as the electrons lose energy – a more robust population for moderate σ values would probably increase the Child-Langmuir enhancement.

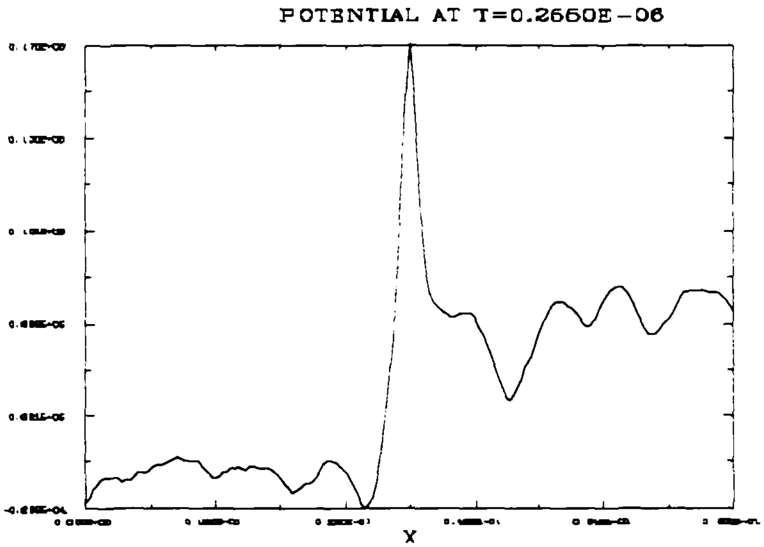

Figure 5b

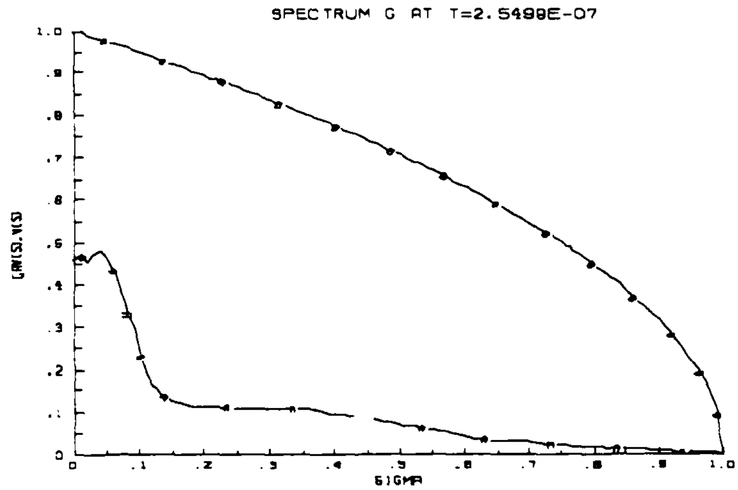

Figure 5c

<u>*Circuit Models for Triode Devices*</u>

One can apply a circuit model to this triode theory when $\omega \ll \omega_{pe}$, and it is worth noting some basic estimates for the electron density and plasma frequency in the switch. The following are lower bounds appropriate near the anode where the electrons move most rapidly:

$$n_e = \beta(8.3 \cdot 10^{10})(\frac{V\ [kV]}{300})(\frac{5}{d\ [cm]})^2 ,$$

$$\omega_{pe} = \beta(1.625 \cdot 10^{10})(\frac{V\ [kV]}{300})(\frac{5}{d\ [cm]})^2 .$$

These timescales for the response of electrons to changes in the ion charge distribution and the electrode surface charge make a very reasonable case for a quasi-static picture. While the timescales observed in REFLEX to recover a low impedance state from some disruption can refine this constraint further, the robustness of the low impedance states observed in the particle code argues for the viability of the near equilibrium picture. The a priori stability of the system could not be assessed from any equilibrium model, but the basic result is that the global field and density profiles demanded by the equilibrium constraint $\nabla \cdot J = 0$ are in fact preferred states of the time evolving system as well. The issue of microstability is quite a different story and here both Vlasov and particle models speak volumes as to the turbulent channels available to the system.

Whatever the details, if one makes the assumption of near equilibrium states, then the value of β determines the triode impedance and requires a V_{AK1} large enough to carry the current supplied by the generator, viz.

$$V_{\mathcal{SWITCH}} = \frac{V_{AK1}}{V_{bank}} = \Delta(\tau)(\frac{\mathcal{I}}{\beta})^{\frac{2}{3}}.$$

This implies a single ODE for $\dot{\mathcal{I}}$, which is of the form

$$\frac{d\mathcal{I}}{d\tau} = \frac{\pi^2}{4}[\mathcal{Q}(\tau) - \Delta(\tau)(\frac{\mathcal{I}}{\beta})^{\frac{2}{3}}] ,$$

with $\tau = t/t_{\frac{1}{4}}$ and $\mathcal{I} = I/I_{bank}$, and $\frac{d\mathcal{Q}}{d\tau} = -\mathcal{I}$. $\Delta(\tau)$ is a measure of the initial operating (reflexing) voltage and is time dependent only because the "anomalous gap closure" is presumed.

V_{SWITCH} is normally steady in the conduction phase, any process in the triode which forces a lower β value precipitates the opening. In modeling the opening phase it is important to increase the speed of the ion motion as the inductive voltage is applied. One finds too slow a decay in the current enhancement if the ions just drift at the speed given by the reflexing voltage. If β^* is the peak current enhancement just prior to opening, then the widening of the gap between the anode and the neutral plasma mass will force the effective β down according to the square of the gap ratio. The application of this notion in the context of our circuit relation results in a time dependent β given by

$$\beta(\tau) \; = \; \frac{\beta^*}{\left[\, 1 \; + \; (\frac{\nu_s \tau}{\xi_o})\sqrt{\frac{V_{AKI}}{V_{Ref}}}\, \right]^2} \; ,$$

where $\nu_s \approx 21.5$ is a measure of the ion drift speed and ξ_o is a measure of the initial gap fraction covered by neutral plasma. Folding all the results together one can get a fair picture of the conduction phase and the opening phase, induced by the quick drop of β as the ions are swept out of the gap. The time delay for the onset of opening is determined experimentally, only more detailed theory can pin down such a number. The initial bank charge is calculated from experimental data, as well as the initial value of β at the observed onset of reflexing. After that the model is on it own, equipped with an estimate for the anomalous gap closure time from the charge exchange calculations mentioned above. The peak current obtained and the peak voltage at opening are not pre-ordained in any way except by the uniqueness of the ODE solution.

The application of this circuit model to a typical shot[10] yields the waveforms shown in Figure 6. Here the peak current predicted is 54 kA while the experiment saw 56 kA; the predicted peak voltage is 634 kV while the experiment saw 560 kV.

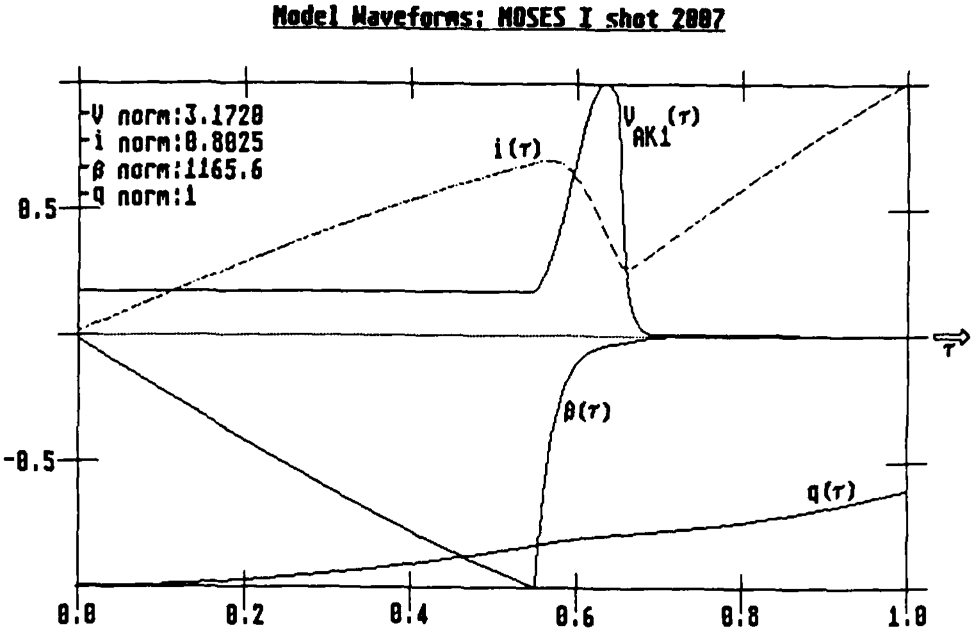

Figure 6

Conclusions

When viewed in the context of the REFLEX particle code work documented elsewhere in these proceedings, the qualitative picture of the reflex switch which arises is both simple and compelling. The device operates at an enhanced current density because neutral plasma plays the role of a conducting medium that effectively shortens the initial gap spacing to two smaller gaps (for a triode) as reflexing electron flux builds up. Each basic notion of the "classical" Reflex Switch model can be partially substantiated by these diverse theoretical approaches and by experiment. Taken as a whole these results show the device to be based on solid physics, but clearly not understood well enough (as yet) to be certain it can fullfill its intended role. We have detailed three points of sensitivity possessed by the reflexing state: ion charge exchange, electron drag from either turbulence or neutral interaction, and ion emission boundary conditions. Each of these may operate along with the "classical" opening mechanism, viz. the shorting of K2 to A, in determining the opening time and, hence, the maximum current. Several modifications to the "classical" picture are implied by our new formulation, in particular

- η_{crit} *is coupled to* Ψ_o *and no longer is purely a function of voltage;*
- *High current, low impedance equilibria persist until the A-K2 potential is less than a range energy* $\approx 10keV$*;*
- *The triode phase space is especially unstable, but the K2 potential will work to keep the hole open;*
- *The spectral convolutions are simplified and can often be performed analytically, yielding quantitative agreement with the observed current enhancement* β.

We have found that the reflexing state is potentially susceptible to the starvation of ion current due to charge exchange or the decay of reflexing electron flux due to electron neutral collisions. If such sensitivity does indeed occur in the laboratory, this would result in a rapid increase in impedance. No experiments yet fielded can preclude any of these ideas but these mechanisms can be quantified with some effort and can help to understand the opening process. Moreover, these additions can be tested in a relevant and cheap circuit model to gain insight and to suggest future experiments. The circuit model clearly operates around the experimentally observed current and voltage traces – without benefit of any free parameters.

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